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SXP 1062: an Evolved Magnetar in a BeXB ?

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Abstract. SXP 1062, a newly discovered Be/X-ray binary in the Small Magellanic Cloud, provides the first example of a robust association with a supernova remnant (SNR). The short age estimated for the SNR qualifies SXP 1062 as the youngest known source in its class, $\tau \approx 10^4$ yr. Here we discuss possible evolutionary scenarios for SXP 1062 in the attempt to reconcile its long spin period, $P = 1062$ s, and short age. Our results indicate that SXP 1062 may host a neutron star born with a large initial magnetic field, typically in excess of $\sim 10^{14}$ G, which then decayed to $\sim 10^{13}$ G.

1. Introduction

Be/X-ray binaries (BeXBs) are the largest subclass of high-mass X-ray binaries (HMXBs) and are both transient and persistent X-ray sources. The latter exhibit a rather flat lightcurve, lower X-ray luminosity ($L \sim 10^{34} - 10^{35}$ erg/s), longer spin and orbital periods ($P \gtrsim 200$ s, $P_{orb} \gtrsim 200$ d; e.g. Reig 2011).

Very recently Hénault-Brunet et al. (2012) and Haberl et al. (2012) reported the discovery of a new BeXB in the Small Magellanic Cloud (SMC). While SXP 1062 has the typical properties of a persistent BeXB ($L \sim 6 \times 10^{35}$ erg/s and $P \sim 1062$ s) what makes this source unique is its robust association with a supernova remnant (SNR). This allows for the first time to estimate the NS age in a BeXB, $\tau \sim 2 - 4 \times 10^4$ yr.

According to the standard picture, there are four stages in the spin evolution of a NS: ejector, propeller, accretor, and georotator (e.g. Lipunov 1992). Once the NS enters the accretor stage, its spin period quickly settles at an equilibrium value, P_{eq} . Ultra-long periods ($P_{eq} > 1000$ s) can be reached without invoking super-strong fields ($B > 10^{14}$ G) if a subsonic propeller stage sets in (Ikhsanov 2007), or a settling regime forms in the accretion flow (Shakura et al. 2012).

The previous argument implicitly relies on the assumption that the present age of the source is long enough for the NS to have entered the propeller stage. Normally, a NS in a BeXB with $B > 10^{12}$ G starts its evolution in the ejector phase. Its duration is $\sim 10^6 (B/10^{12} \text{ G})^{-1} (\dot{M}/10^{15} \text{ g/s})^{-1/2}$ yr. This is comfortably below the lifetime of the Be companion. In the case of SXP 1062, however, it would be impossible for the NS to enter the propeller stage in a time as short as a few $\times 10^4$ yr, the estimated SNR age, for typical values of B and \dot{M} . The accretion rate in SXP 1062 is $\dot{M} = L/\eta c^2 \sim 6 \times 10^{15}$ g/s for an efficiency $\eta = 0.1$, so this points to a highly magnetized NS, with an initial magnetic field substantially above 10^{12} G. Here we summarize the results presented in Popov & Turolla (2012) and add some new considerations.

2. Spin Evolution in SXP 1062

In the ejector phase the light cylinder radius, R_{lc} , is typically smaller than the gravitational capture radius, $R_G = 2GM/V^2$, where V is the velocity of matter far from the star ($M_{NS} = 1.4M_\odot$, $R_{NS} = 10$ km and moment of inertia $I = 10^{45}$ g cm² are assumed henceforth). The transition to the propeller stage occurs when the ram pressure, $P_{dyn} = \rho V^2/2$, balances the outgoing flux of electromagnetic waves and relativistic particles $P_{PSR} = \dot{E}/(4\pi R^2 c)$, at R_G (\dot{E} is the rotational energy loss rate of the pulsar). The critical period for the transition follows by requiring that $P_{dyn}(R_G) = P_{PSR}(R_G)$, together with the standard expression for magneto-dipole losses and mass conservation,

$$P_{ej} = 2\pi \left(\frac{4}{3} \frac{B^2 R_{NS}^6}{\dot{M} V c^4} \right)^{1/4} \sim 0.31 V_{300}^{-1/4} \dot{M}_{16}^{-1/4} B_{12}^{1/2} \text{ s}. \quad (1)$$

From the magneto-dipole formula, assuming constant B and very short initial period, it follows that

$$\tau_{ej} = \frac{3Ic^3 P_{ej}^2}{16\pi^2 B^2 R_{NS}^6} \sim 1.5 \dot{M}_{16}^{-1/2} V_{300}^{-1/2} B_{12}^{-1} \text{ Myr}. \quad (2)$$

The dipole field in a wind-fed NS has been estimated by Shakura et al. (2012) under the assumption that the star is spinning at the equilibrium period

$$B_{12} \sim 8.1 \dot{M}_{16}^{1/3} V_{300}^{-11/3} \left(\frac{P_{1000}}{P_{orb 300}} \right)^{11/12} \text{ G}. \quad (3)$$

This gives $\tau_{ej} \sim 0.2$ Myr for SXP 1062, a factor 10 longer than the SNR age.

Within this framework, an obvious possibility to shorten the ejector phase in SXP 1062 is to invoke a higher dipole field. However, if the present field is that given by the previous expression this implies that B must have been stronger in the past and then decayed to its present value (see e.g. Pons et al. 2009; Popov et al. 2010; Turolla et al. 2011).

The period evolution in the ejector stage is governed by magneto-dipolar losses and we adopted the simplified model of Aguilera et al. (2008) for the evolution of B . The NS enters the propeller phase as soon as the dynamical pressure exerted by the incoming material overwhelms the pulsar momentum flux at the gravitational radius. Spin-down is expected to be very efficient in the propeller phase, so its duration is quite short. Finally, to follow the period evolution in the accretor stage we assume the settling accretion regime recently proposed by Shakura et al. (2012).

We solved numerically the equation for the period evolution in the three stages starting from $t_0 = 0.01$ s with an initial period $P_0 = 0.01$ s. The accretion rate was fixed to $\dot{M} = 6 \times 10^{15}$ g/s, together with $P_{orb} = 300$ d, $V = 300$ km/s, Ohmic decay timescale $\tau_O = 10^6$ yr, and relic field 8×10^{12} G. Figure 1 illustrates the results for typical runs with different values of the initial field B_0 . The main result is that a quite large initial field is required in order for SXP 1062 to enter the propeller phase (and quickly start accreting) in a time as short as a few $\times 10^4$ yr. For the case at hand it has to be $B_0 > 10^{14}$ G for this to occur. However, the result is not very sensitive to the actual choice of the Hall decay timescale, τ_H , and angle between spin and magnetic axis, α . The conclusion that SXP 1062 harbours an initially strongly magnetized NS seems therefore quite robust.

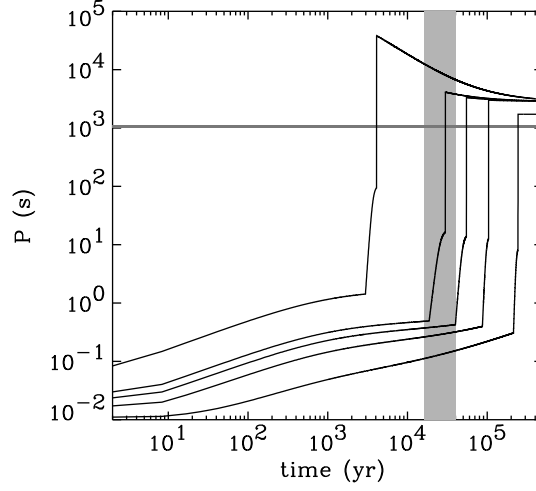


Figure 1. The spin period evolution for $B_0 = 4 \times 10^{14}$, 10^{14} , 7×10^{13} , 4×10^{13} , 10^{13} G (solid lines, from top to bottom). The shaded areas mark the age and period of SXP 1062 with the respective uncertainties.

3. Discussion

Normally, one expects that accreting X-ray pulsars spin close to their equilibrium period. However, for a young system like SXP 1062 this appears far from granted. Haberl et al. (2012) reported a large spin-down rate for SXP 1062 ($\dot{P} \sim 95$ s/yr) which may suggest that P_{eq} has not been reached yet. According to the standard evolutionary scenario (Lipunov 1992), the (maximum) spin-down rate in the accretor stage is $\dot{P} \sim 2\pi B^2 R_{NS}^6 / (GMI)$ which implies $B \sim 3 \times 10^{14}$ G for $\dot{P} \sim 100$ s/yr. On the other hand, if Shakura et al. spin-down formula is used to estimate the magnetic field, a much lower value is obtained, $B \sim 10^{13}$ G, very close to what is predicted assuming that the source spins at the equilibrium period. This supports a picture in which the NS actually rotates close to P_{eq} . A further argument in favor of this is the very short duration of the spin-down phase in the accretor stage, which makes it very unlikely to catch the source in this state. Our conclusion is that both the young age and the large spin-down rate of SXP 1062 argue in favor of an initially highly magnetic NS which experienced field decay.

Alternative scenarios to explain the long period and short age of the source can be envisaged. For instance, Haberl et al. (2012) suggested that the NS could have been born with an initial period $\gg 0.01$ s. The value of P_0 can be evaluated by requiring that the end of the ejector stage is reached in less than the source age, and it turns out to be ~ 1 s for $B \sim 10^{13}$ G. If this is the case no field decay is required. Another possibility is that the NS could have been surrounded by a debris disc, which could also lead to rapid spin-down and large period, as suggested for the enigmatic source RCW 103 (De Luca et al. 2006; Li 2007) (see also a recent e-print by Yan et al. (2012)). Although this remains a possibility worth of further investigations, preliminary calculations in-

dicates that the disc has to be quite massive ($\gtrsim 10^{-2} M_{\odot}$) for this to work with a field $\sim 10^{13}$ G.

If SXP 1062 indeed contains an initially strongly magnetized neutron star, then studies of this system can shed light on the origin of magnetars. Chashkina & Popov (2012) have recently derived estimates of the B-field in HMXBs using Shakura et al. model and no evidence of ultra-high fields was found. A very recent, quite robust case for a possible magnetar in a binary system was made by Reig et al. (2012) (see also Reig et al., this proceedings). According to eq. (3), in fact, the field of the NS in the BeXB 4U 2206+54 ($P \sim 5560$ s, $\dot{M} \sim 3 \times 10^{15}$ g/s, $V \sim 350$ km/s, $P_{orb} \sim 10$ d) is about 4×10^{14} G. The original estimate in Reig et al. (2012) also provides similar values. Bogomazov & Popov (2009) studied several options to produce a rapidly rotating stellar core just before the collapse, so that the dynamo mechanism can operate. This turns out to be possible, due to tidal synchronization, in a close binary with an orbital period $\lesssim 10$ d. Using the on-line tool for binary evolution (<http://xray.sai.msu.ru/sciwork/scenario.html>; Lipunov et al. 1996), we find that a binary with initial separation $30 R_{\odot}$ and masses 27 and $9 M_{\odot}$ can match the requirements. Before the SN explosion the orbital period is about 2 d, and becomes $\lesssim 10$ d after (the value and direction of the kick is important in fixing the orbital period). Other combinations of parameters are possible, too. What is noticeable is that in such a system tidal synchronization can result in a rapidly rotating core which later produces a magnetar.

Despite magnetars were searched for in binary systems long since, only very recently promising candidates have been proposed. Further studies of magnetar candidates in binaries will be crucial in shedding light on the origin of these peculiar objects.

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